Letters to ESEX

Climate-invariant area–slope relations in channel heads initiated by surface runoff

Krista K. Garrett* and Ellen E. Wohl
Department of Geosciences, Colorado State University, Fort Collins, CO USA

ABSTRACT: We use a dataset of 38 field-mapped channel heads from a semi-arid environment in western Colorado to examine relationships between contributing drainage area ($A$) and local hillslope gradient ($\theta$) in relation to dominant process of initiation (surface runoff versus subsurface flow). Channel heads resulting primarily from subsurface flow have significantly greater values of $A$, longer basin lengths, and shallower local gradients than channel heads resulting primarily from surface runoff. We also compare the data from western Colorado to six analogous datasets from more humid regions in other portions of the United States and in southeast Australia. Comparison of the confidence intervals for the exponent values of $A$–$\theta$ regression lines reveals that the confidence intervals for the exponent of western Colorado channel heads with both surface and subsurface flow overlap with the confidence intervals for the exponent of all other datasets. This suggests that $A$–$\theta$ relationships do not differ significantly between diverse geographic locations.

KEYWORDS: channel heads; channel initiation; area–slope relations; semi-arid environments

Introduction

Headwater streams (first to third order; Strahler, 1952) are increasingly studied as essential components of watersheds, but remain poorly understood. These streams constitute the majority of the total channel length in a network (Downing et al., 2012) and therefore provide the entry point for most water and sediment in the network (Wohl, 2010). As such, delineating and understanding headwater channel initiation is important for managing headwater stream systems (Jaeger et al., 2007).

One of the more difficult tasks is locating the channel head. A channel head defines the upstream-most point of a longitudinally continuous channel delineated by the presence of a channel bed and banks (Dietrich and Dunne, 1993), where the unchanneled hillslope changes to the channel network (Montgomery and Dietrich, 1988, 1989). The channel head does not necessarily coincide with stream flow; the stream head is defined as the location below which perennial flow occurs (Jaeger et al., 2007). Channel heads and stream heads are poorly represented in standard-resolution digital elevation models (DEMs), difficult to detect in remote sensing imagery if vegetation is present, and require substantial effort to map in the field. However, their delineation influences estimation of parameters such as channel length and drainage density, and influences management designed to protect riparian buffers and aquatic resources.

Channel initiation and the location of the channel head can reflect surface runoff, preferential subsurface flow, or a combination of both processes (Dietrich and Dunne, 1993). Channel initiation commonly occurs in topographically convergent zones, although the relative importance of topography and stratigraphy in concentrating flow varies between channel heads resulting primarily from surface runoff and seepage. Channels initiated by surface runoff develop through rilling when the source basin reaches some critical length or drainage area such that sufficient flow has concentrated to initiate erosion (Horton, 1945; Dietrich and Dunne, 1993), a threshold that reflects surface resistance as influenced by variables such as cohesion, vegetation, and grain size (Istanbulluoglu et al., 2002). Channels initiated by subsurface processes form when substrate heterogeneities concentrate subsurface flow that returns to the surface, creating sapping, piping, and seepage erosion (Jones, 1971; Dunne, 1980).

The average location of channel initiation on a hillslope is sometimes delineated based on inflection points in slope profiles, but field data remain critical for constraining the threshold at which channels initiate (Montgomery and Foufoula-Georgiou, 1993). Field-based studies consistently indicate relationships between topographic parameters and channel initiation points. Contributing drainage area ($A$) and/or basin length ($L$) decrease with increasing local slope ($\theta$) at the channel head (Montgomery and Dietrich, 1989, 1992; Dietrich et al., 1992; Prosser and Abernethy, 1996; Roth and La Barbera, 1997; Jefferson and McGee, 2013), although substantial influence by subsurface flow tends to obscure $A$–$\theta$...
relations (Anderson et al., 1997; McDonnell, 2003; Adams and Spotila, 2005; Hattanji et al., 2006; Jaeger et al., 2007). Several studies note the large variability in $A - \theta$ relations within and between geographic regions (e.g. Bischetti et al., 1998; Tarolli and Dalla Fontana, 2009; Henkle et al., 2011), and Montgomery and Dietrich (1988) suggest that drier regions tend to have larger values of $A$ for the same value of $\theta$. However, field data for channel heads in arid and semi-arid regions are lacking.

Previous studies using field mapping to examine spatial patterns of channel initiation have focused largely on humid-temperate regions with continuous vegetation cover (e.g. Montgomery and Dietrich, 1988, 1989; Bischetti et al., 1998; Henkle et al., 2011; Orlandini et al., 2011; Julian et al., 2012; Jefferson and McGee, 2013). Consequently, understanding of the relative importance of surface and subsurface processes and spatial distribution of channel heads in drier regions remains limited. In this study, we supplement existing understanding of the spatial patterns of channel heads by examining a dataset from semi-arid regions with discontinuous vegetation cover in western Colorado, USA. We hypothesize that channel heads resulting primarily from subsurface flow have larger contributing drainage area, longer basin length, and shallower local gradient than channel heads initiated primarily by surface runoff. We also hypothesize that relationships between channel head location and topographic parameters at the western Colorado study site will differ significantly from such relationships in wetter regions.

Regional Setting

The channel heads identified in this study are located on the Uncompahgre Plateau in the Uncompahgre National Forest (UNF) and the Dominguez Canyon Wilderness Study Area (Figure 1). The geology at the crest of the Plateau primarily consists of Triassic and Jurassic sedimentary rocks, predominantly in the Chinle Formation, Wingate Sandstone, and Morrison Formation (Green, 1992). The elevations of study sites on the Uncompahgre Plateau range from 2182 to 2692 m. Climate is semi-arid, with a mean annual precipitation of 288 mm (Western Regional Climate Center, 1997–2008). This climate supports vegetation communities that include sagebrush (Artemisia spp.) and pinyon pine (Pinus edulis)-juniper (Juniperus spp.) forests at lower elevations, with ponderosa pine (Pinus ponderosa) and mixed conifer forests and aspen (Populus tremuloides) stands at higher elevations (USDA Forest Service, 1991; Binkley et al., 2008). Many of the study sites have discontinuous vegetation and patches of bare soil. Limited data are available for hydroclimatic patterns on the western slope of the Rocky Mountains. Surface runoff likely results from multiple flow-generating mechanisms similar to those on the eastern side of the Rocky Mountains, where surface runoff is dominated by spring snowmelt at elevations above 2300 m and by convective rain events at elevations below 2300 m (Jarrett, 1990).

Land uses in the study area include non-motorized recreation, off-highway vehicle (OHV) use, historical and contemporary cattle grazing, and timber harvesting. The last major landscape-scale wildfire documented in historic records occurred in 1879 (Binkley et al., 2008). We chose the least impacted sites available when mapping channel heads for this study.

Methods

Field methods

Channel heads were selected to represent a range of elevation and vegetation, local slope gradients, and underlying lithology characteristic of the field area. Each channel head was mapped using a hand-held global positioning system (GPS; Garmin eTrex, ±3 m horizontal accuracy). We recorded any evidence of surface or subsurface flow channel initiation, such as amphitheater-shaped channel heads or visible surface runoff and assigned each channel head to a surface or subsurface initiation category (Supporting Information Figure S1).

Figure 1. Map of the study region located in the Uncompahgre National Forest (UNF), showing the locations of the mapped channel heads on a hillshade created using a 10-m digital elevation model (DEM) of the region. White triangles indicate channel heads with evidence of subsurface flow initiation; black triangles indicate channel heads with evidence of initiation due to surface runoff.
Additionally, the presence and type of vegetation cover was categorized based on the presence of trees, shrubs, graminoids, and forbs.

Spatial analysis methods

The channel head locations were imported to ArcGIS and projected on a 10-m DEM of the region. Sinks in the DEM were filled and the DEM was used to create a flow accumulation raster. The value of the pixel containing the channel head point was used to determine the contributing drainage area of each channel head. Some of the channel head points did not fall exactly on a pixel indicating flow lines, likely due to error in the GPS point collection and/or error in the creation of the flow accumulation raster using a coarse resolution DEM. These points were moved to the closest flow accumulation pixel. The local basin slope was determined by taking the difference between the elevation of the DEM pixel immediately upstream of the channel head and the channel head’s elevation, and dividing this by 10 m, which is the width of a pixel (Jaeger et al., 2007). The basin length, from the drainage divide to the channel head location, was calculated using the flow length tool in ArcGIS. The flow length tool calculates the longest distance a drop of water would travel from the drainage divide to the selected pixel; this value is used as the length of the basin upstream of the channel head.

Other datasets

We compare the channel heads from western Colorado with published channel head datasets from diverse climates and lithologies, including US sites in the Colorado Front Range (higher elevation and wetter sites on the eastern side of the Rocky Mountains in Colorado; Henke et al., 2011), North Carolina (Jefferson and McGee, 2013), the Mid-Atlantic region, which here includes the Appalachian Plateau and the Piedmont (Julian et al., 2012), and central California (Montgomery and Dietrich, 1989), as well as sites in southeast Australia (Prosser and Abernethy, 1996). All of these regions receive greater mean annual precipitation than western Colorado (Table I). Local slope–drainage area relationships were published for North Carolina, central California, and southeast Australia. We developed relationships for published data from the Colorado Front Range and Mid-Atlantic regions.

The data used to develop the equation for southeast Australian channel heads were not available for this study.

Statistical methods

In order to evaluate channel initiation, channel heads were compared based on local gradient, drainage area, basin length, lithology, elevation, and surface or subsurface flow. All statistical analyses were performed using the R statistical package and a confidence level of 95%.

The sample population was tested for normality using visual methods, such as histograms and qq plots, and the Shapiro–Wilk test for normality. None of the variables had normal distributions; multiple transformations were considered, but none provided satisfactory normality. Because of this, non-parametric tests were used to analyze the data. Boxplots and the non-parametric Wilcoxon Rank Sum test were used to compare the variables drainage area, local gradient, and basin length between subsurface and surface flows. The Wilcoxon Rank Sum test is considered an approximate test of the medians to determine whether two samples come from the same population (Ott and Longnecker, 2010).

The data collected from the western Colorado study region were plotted on a scatterplot of gradient (x-axis) versus contributing drainage area (y-axis). Data from other studies were plotted on the same axes in order to compare between study regions and examine the data for regionally significant trends. Quantitative relationships between these variables were also considered. Linear regression of the log-transformed data was conducted; the coefficients were then untransformed to yield the relationship equation in the form $A = \lambda \theta^b$, where $\lambda$ is a constant coefficient. Relationship equations were compared using the 95% confidence intervals of the coefficients. Overlapping confidence intervals indicate no statistically significant difference between two relationships.

Results

A total of 38 channel heads were selected for analysis. Twenty-five have underlying sandstone lithology and 13 are underlain by shale (Supporting Information Table S1). Ten of the channel heads have evidence of subsurface flow (e.g. amphitheater headcut); the remaining 28 have evidence of initiation due to surface runoff. Channel heads underlain by sandstone include

Table 1. Precipitation values, number of channel heads surveyed, predominant vegetation, dominant inferred precipitation type leading to channel initiation, and primary published reference for each dataset included in analyses

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Mean annual precipitation (mm)</th>
<th>Number of channel heads</th>
<th>Predominant vegetation</th>
<th>Dominant inferred precipitation type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Colorado</td>
<td>288</td>
<td>38</td>
<td>Pinyon-juniper forest, conifer forest</td>
<td>Mixed</td>
<td>This study</td>
</tr>
<tr>
<td>Colorado Front Range</td>
<td>430–1000</td>
<td>78</td>
<td>Conifer forest</td>
<td>Mixed</td>
<td>Henke et al., 2011</td>
</tr>
<tr>
<td>North Carolina</td>
<td>1140–1180</td>
<td>100</td>
<td>Mixed hardwood-conifer forest</td>
<td>NA&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Jefferson and McGee, 2013</td>
</tr>
<tr>
<td>Appalachian Plateau</td>
<td>1170–1203</td>
<td>7</td>
<td>Mixed mesophytic forest</td>
<td>NA&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Julian et al., 2012</td>
</tr>
<tr>
<td>Piedmont</td>
<td>1084–1139</td>
<td>78</td>
<td>Mixed mesophytic forest</td>
<td>NA&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Julian et al., 2012</td>
</tr>
<tr>
<td>Central California</td>
<td>760</td>
<td>63</td>
<td>Grasslands</td>
<td>NA&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Montgomery and Dietrich, 1989</td>
</tr>
<tr>
<td>Southeast Australia</td>
<td>500&lt;sup&gt;a&lt;/sup&gt;</td>
<td>—</td>
<td>Grasslands</td>
<td>Convective</td>
<td>Prosser and Abernethy, 1996</td>
</tr>
</tbody>
</table>

<sup>a</sup>Only median annual precipitation reported.

<sup>b</sup>Dominant inferred process not reported in paper.
sites with surface and subsurface flow, whereas channel heads underlain by shale initiate only through surface flow.

Comparison of channel heads initiated by surface and subsurface flow

We find statistically significant differences (p-value < 0.05) between the contributing areas, basin lengths, and gradients of channel heads with evidence of subsurface flow and channel heads with evidence of surface runoff (Figure 2, Table II). Channel heads with evidence of subsurface flow have statistically larger contributing drainage areas, longer basin lengths, and shallower local gradients than channel heads with evidence of surface runoff.

The effect of gradient on contributing area was examined by plotting the data points on a scatterplot of local gradient versus contributing area (Figure 3). Regression lines were fitted to the channel head data, using the logarithm of contributing drainage area as the dependent variable regressed against the logarithm of local gradient. Relationship equations were developed for all of the channel heads, for channel heads with evidence of subsurface flow, and for channel heads with evidence of surface runoff. An inverse relationship across all channel heads is observed:

$$A = \frac{\lambda \theta^{1.02}}{C_0}$$

where $\lambda = 1097\ m^2$ with an adjusted $R^2$ value of 0.46 and a p-value < 0.0001. It is apparent from this plot and the slope of the fitted regression line that, as local hillslope gradient

<table>
<thead>
<tr>
<th>Flow type</th>
<th>Adjusted $R^2$ value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western Colorado</td>
<td>0.46</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Subsurface</td>
<td>&lt;0.01</td>
<td>0.87</td>
</tr>
<tr>
<td>Surface</td>
<td>0.53</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Front Range</td>
<td>0.11</td>
<td>0.01</td>
</tr>
<tr>
<td>Central California</td>
<td>0.75</td>
<td>—</td>
</tr>
<tr>
<td>North Carolina</td>
<td>0.65</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Appalachian Plateau</td>
<td>0.55</td>
<td>0.04</td>
</tr>
<tr>
<td>Piedmont</td>
<td>0.24</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Southeast Australia</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Figure 2. Boxplots of (A) contributing drainage area, (B) basin length, and (C) local gradient grouped by flow type at the channel head. The bottom and top of each box represents the first and third quartiles; the line between them represents the median. The ends of the whiskers represent the minimum and maximum. The points located outside the whiskers are considered extreme values and the asterisks denote the mean of each group.
increases, the contributing drainage area decreases. A second significant relationship was developed between the local gradient and contributing area for channel heads with evidence of surface runoff:

\[ A = \frac{\lambda \theta}{C_0} \]

where \( \lambda = 920 \text{ m}^2 \) with an adjusted \( R^2 \) value of 0.53 and the \( p \)-value < 0.0001. A third relationship equation was developed for channel heads with subsurface flow, but this relationship is not significant:

\[ A = \frac{\lambda \theta}{C_0} \]

where \( \lambda = 21270 \text{ m}^2 \) with an adjusted \( R^2 \) value of approximately zero and a \( p \)-value of 0.87.

Comparison of western Colorado channel heads to other regions

The channel head data for all datasets are plotted on a graph of gradient versus contributing area (Figure 4) and the regression equations are plotted for each of these datasets. For the purposes of comparison, the Mid-Atlantic dataset is divided according to location. Julian et al. (2012) found that in this region, only channel heads located in the Appalachian Plateau and the Piedmont had statistically significant relationships between gradient and contributing area; data from these two regions are used in this comparison. The coefficients, exponents, and corresponding confidence intervals are presented in Table III. The exponent values are most important, as they dictate the slope of the regression line. Comparison of the confidence intervals for the exponent values reveals that the confidence intervals for the exponent of channel heads with both surface and subsurface flow overlap with the confidence intervals for the exponent of all other datasets. This indicates that these relationships are not statistically significantly different based on location. The coefficients of the regression lines may display different values and thus reflect differences in contributing area for a particular local slope, but the rate of change is consistent among the datasets.

Discussion

Influence of flow pathways on channel initiation

Our finding of an inverse relation between \( A \) and \( \theta \) that is significant for channels resulting from surface runoff but not significant for channels initiated by subsurface flow agrees with previous research in wetter environments (e.g. Montgomery and Dietrich, 1988, 1989; Prosser and Abernethy, 1996).

Statistical differences between \( A \), \( L \), and \( \theta \) of channel heads with evidence of initiation resulting from subsurface versus surface flow, as well as separation of surface- and subsurface-initiated channel heads on an \( A-\theta \) plot (Figure 3), indicate that the type of flow initiating a channel greatly influences the location of the channel head. Consequently, using standard \( A-\theta \) equations to predict the locations of channel heads initiated by subsurface flow introduces inaccuracies and uncertainty. The regression line for the subsurface data on Figure 3 is not statistically significant, likely due to the small sample size (\( n = 10 \)) and wide range of variability. Despite this, the regression line provides a good representation of the differences between channel heads with evidence of subsurface and surface flow. Consequently, we consider it important to distinguish the type of flow initiating channel formation when examining or attempting to predict channel head locations.

Comparison of western Colorado channel heads to other regions

Based on the findings of Henkle et al. (2011), we expected contributing area and gradient to have less influence on
channel initiation in western Colorado than in wetter regions and we expected the $A-\theta$ relationship to differ from relationships in more humid regions. Simple linear regression equations for $A-\theta$ indicate that the relationships for western Colorado channel heads are not statistically different from similar relationships for other study regions. The adjusted $R^2$ values for the $A-\theta$ relationship for all western Colorado channel heads and for those with evidence of surface runoff are similar to the $R^2$ values from other, more humid regions (Table II), indicating that contributing area and gradient strongly influence the location of channel initiation, regardless of aridity.

We interpret these results as indicating that broadly applicable relationships could be developed for channel heads initiated by surface runoff in diverse environments. The datasets from previous work used in this study did not distinguish between channel heads initiated by surface or subsurface flow. It is possible, based on these results, that regional differences in climate and lithology have minimal effect on the location of channel heads. Determining whether a broadly applicable relationship exists between contributing drainage area and local gradient is worth further investigation.

**Limitations to these analyses**

The results presented here represent channel conditions at a single point in time. The location of channel heads migrates in the aftermath of large disturbances such as fires or floods (Kirkby et al., 2003; Wohl, 2013). Many of the channel heads selected for this study are located in ephemeral or intermittent streams, and as such are likely subject to unrecorded flash flooding. The last major landscape-scale fire in this region occurred over a century ago (Binkley et al., 2008). The history of disturbances, whether recent or historical, can cause variability in the location of channel heads, but this uncertainty was not accounted for in this study.

**Conclusion**

The analyses presented here partly support our initial hypotheses. As hypothesized, channel heads resulting primarily from subsurface flow have larger contributing drainage area, longer basin length, and shallower local gradient than channel heads initiated primarily by surface runoff. Channel heads resulting from surface runoff also have a significant inverse $A-\theta$ relation, whereas the relationship for channel heads resulting from subsurface flow is not significant. The data from western Colorado did not support our second hypothesis that $A-\theta$ relations for this semi-arid region would differ significantly from those of wetter regions. This finding is particularly important because it suggests that, despite scatter in the values of $A$ and $\theta$ from regions with diverse climates, consistent relations may exist that can be used to predict the locations of channel heads resulting from surface runoff.

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**References**


**Supporting Information**

Additional Supporting Information may be found online in the supporting information tab for this article.